



Additive Manufacturing of Mould Inserts with Mirror-like Surfaces

Biondani, Francesco Giuseppe; Bissacco, Giuliano; Tang, Peter Torben; Hansen, Hans Nørgaard

Published in:
Procedia CIRP

Link to article, DOI:
[10.1016/j.procir.2017.12.097](https://doi.org/10.1016/j.procir.2017.12.097)

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Biondani, F. G., Bissacco, G., Tang, P. T., & Hansen, H. N. (2018). Additive Manufacturing of Mould Inserts with Mirror-like Surfaces. *Procedia CIRP*, 68, 369-374. <https://doi.org/10.1016/j.procir.2017.12.097>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

19th CIRP Conference on Electro Physical and Chemical Machining, 23-27 April 2018, Bilbao, Spain

Additive manufacturing of mould inserts with mirror-like surfaces

Francesco Biondani^{a*}, Giuliano Bissacco^a, Peter Torben Tang^b, Hans Nørgaard Hansen^a

^aDepartment of Mechanical Engineering, Technical University of Denmark, Produktionstorvet, DK-2800 Kongens Lyngby

^bIPU, Nils Koppels Alle, DK-2800 Kongens Lyngby

* Corresponding author. Tel.: +45 45254733. E-mail address: frgbio@mek.dtu.dk

Abstract

Selective laser melting (SLM) is often applied in the production of steel moulds with high wear resistance and conformal cooling channels for advanced thermal management. The surface finishing of such moulds is crucial, especially if it is intended for the moulding of plastic parts with aesthetic functionality. The surface quality of such metal 3D printed moulds is typically refined by means of subsequent material removal processes, but this is often hindered by residual porosity and inhomogeneity in the metal structure of the 3D-printed part.

In this paper an indirect tooling process chain for production of mould inserts is proposed. The process chain aims at exploiting the good replication capability of electroformed nickel, to copy mirror-like substrates. The bulky part of the insert is produced by means of SLM that shows a considerably higher material deposition rate. The thermal input is controlled throughout the process chain to prevent deleterious grains growth in the nickel layer.

The roughness of the nickel surface is measured after the selective etching of the substrate and compared with the substrate roughness before the nickel deposition, showing good replication of the master surface. The proposed process chain overcomes the problems related to the deposition of thick electroformed coatings by coupling electroforming with higher output additive processes such as SLM - that furthermore allows the introduction of cooling channels in close contact with the mould surface.

© 2018 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the scientific committee of the 19th CIRP Conference on Electro Physical and Chemical Machining

Keywords: Additive Manufacturing, Electroforming, Mirror-like Surfaces

1. Introduction

Moulds are essential requirements in replication processes such as injection moulding, hot embossing, casting and many others. The primary function of a mould is shaping, providing the geometrical characteristics that will allow to fulfill the design purpose of the produced parts. Moulds are produced by means of different process chains, encompassing design phase, material choice, shaping and assembly of the tool and quality control.

Complexity, length of the process chain and performance of the tool will determine which process chain is viable for a given final product.

1.1. Additive manufacturing in moulds production

Additive manufacturing finds in moulds and dies production one of its most successful application. The layer-by-layer

building fashion is exploited for production of free form geometries and conformal cooling channels. Especially in plastic injection moulding conformal cooling channels have proven of being able to reduce the cycle time of plastic products and the defects occurrence rate [1]. Additive manufacturing is particularly suitable in all those applications in which surface finishing is not a strict concern. State of the art additive manufacturing techniques cannot compete with the surface finishing and accuracy given by conventional material removal processes: inhomogeneity on the part, voids and thermal distortions are detrimental for the performance of the final mould [2] (see figure 1 top). In those cases, extensive post process is required and the time span for mould production, even using the so-called rapid manufacturing techniques, approaches the conventional tooling process chains [3].

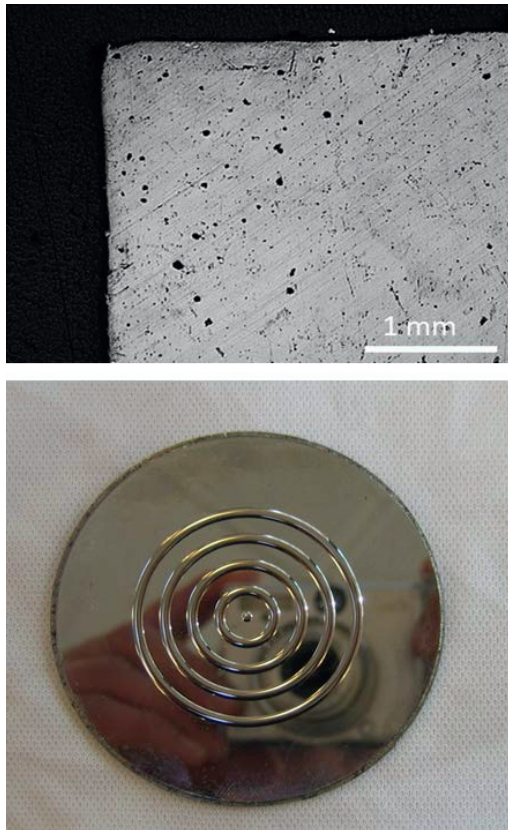


Fig. 1. Top: residual porosity on a SLM part during a screening for optimal process parameters. The part was printed using a copper-based alloy in which high density is difficult to achieve. Bottom: Electroformed nickel mould for precision glass moulding [4].

1.2. Electroforming in moulds production

Electroforming consists in “*production of article by electrodeposition upon a mandrel and subsequent separation of the deposit*” as defined by ASTM B832-93.

In tooling process chains, electroformed moulds are, for the majority of the cases, produced by deposition of a thick layer of nickel following a so-called indirect tooling process, [5] (see also figure 2). A master is produced with the opposite shape of the final tool. Nickel (or another metal) is electroplated on the master and, after reaching an appropriate thickness, the master is chemically dissolved and the nickel deposit is used as tool. In some cases the deposit is separated from the master mechanically, however this is not always possible without damaging the surfaces.

Electroformed nickel coatings are able to copy the master's surface with nanometric accuracy, therefore electroforming is often involved in production of mould for lenses (see figure 1 bottom), microfluidic channels, CD/DVD/Blu-ray stampers and other micro/nano engineering applications [6], [7], [8], [4], [9]. Use of nickel moulds in high wear applications, such as metal drawing and forming, is hampered by the maximum achievable hardness of the electroformed coatings. Nickel coatings can reach hardness values in the range of 400-500 HV when deposited by electroplating. For applications in polymer

injection moulding, such hardness is sufficient for stable and reliable production.

Even though a 50 μm coating may be sufficient for wear resistance purpose, thicker coatings are often applied for safe handling and for safe utilization during injection moulding or other replication processes.

The growth rate of electrodeposited metals is in the range from 10 up to 100 $\mu\text{m/h}$, therefore thick coatings (several millimeters or more) require a deposition time measured in weeks - and comes along with increased cost and risk of failures: the coating can separate from the master, bubbles can get trapped inside the deposit and uneven current distribution may create unwanted deposit growth.

2. Four steps process chain for mould production

Both additive manufacturing and electroforming face limitations in term of surface quality for the former and excessive process time for the latter. The process chains proposed in this paper aims at combining the surface quality achievable with electroforming with the higher deposition rate and geometrical freedom of the additive manufacturing techniques.

The main steps of the process chain are:

- Diamond machining or polishing of a suitable material to fabricate a master with the opposite shape of the tool that has to be produced
- Electrodeposition a nickel layer with a thickness in the order of 500 μm over the master
- Introduction of a metallic buffer layer on top of the electrodeposited nickel
- Growth of the rest of the mould by means of additive manufacturing on the back side of the buffer layer

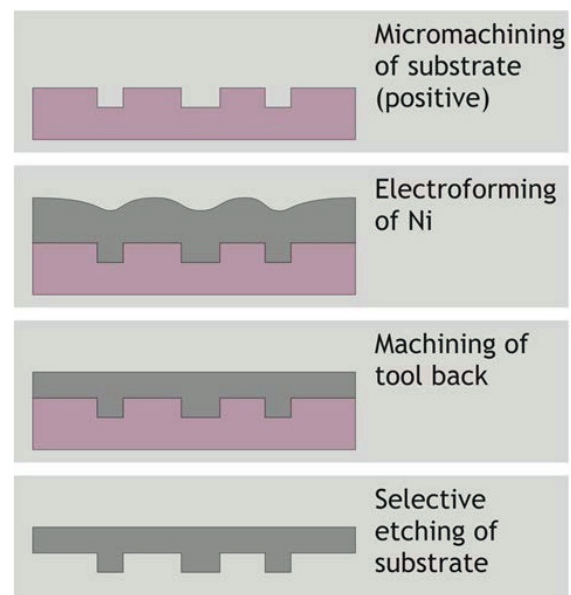


Fig. 2. One example of indirect tooling [4]

2.1. Advantages of the proposed process chain

Mirror-like surfaces can easily be achieved by means of diamond machining of suitable substrate materials such as aluminum, copper and acrylic resins or using other processes such as polishing.

The application of the proposed process chain allows to stop the electroforming process after deposition of 400-500 μm of nickel to assure a proper wear resistant layer. The rest of the mould, produced via 3D printing on top of the nickel layer, provides the needed mechanical support and can incorporate feature for thermal management such as conformal cooling channels.

2.2. Control of the thermal input

Combining a thermal deposition process (SLM) with electroforming presents some engineering challenges. The thermal input of the 3D printing process has to be carefully controlled in order to prevent melting of the electroformed layer. Considering selective laser melting (SLM), for example, the extension of the melting pool and the heat affected zone propagate on the already printed metal layers. If the temperature increases over the melting or even over the recrystallization point of the nickel coating, irregular grain growth will take place and the original nano scale roughness of the coating will be lost [10].

In fact, during the machining operation, the grains composing the polycrystalline matrix of the material are cut through by the cutting edge of the tool along the cutting plane.

If the temperature of the material exceed the recrystallization temperature, the grains will begin to coalesce - and will increase their size in an uncontrolled manner, growing in and out of the initial cutting plane.

This deleterious growth affects the surface roughness and micro hardness and can be detected by means of roughness and hardness measurements of the variation of the surface properties after the master removal [4].

In order to counteract this problem a buffer layer is interposed between the nickel deposit and the 3D printed structure.

This layer will effectively shield the top of the nickel surface from a direct contact with the laser of the metal 3D printer, point in which the formation of the melting pool occurs and extreme temperature are reached.

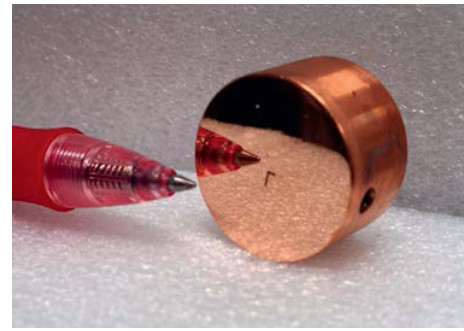
A low thermal input process, such as thermal spraying, is used to deposit the shield layer, in order to prevent - or significantly reduce - the recrystallization process.

3. Experimental procedure

In the current section, the manufacturing steps for the production of a proof-of-concept mould insert for injection moulding are briefly described.

3.1. Choice of master

Appropriate choice of the master material is fundamental for the success of the process chain.



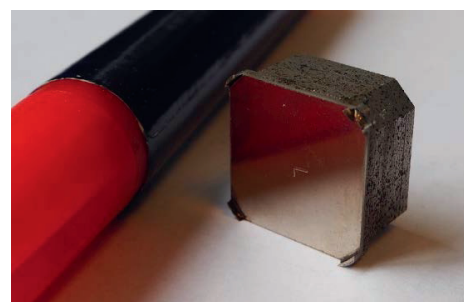
(a)



(b)



(c)



(d)

Fig. 3. Proposed process chain: (a) master surface after machining and finishing; (b) electroformed nickel coating; (c) deposition of thermal sprayed layer and 3D printed structure; (d) finished mould insert after selective etching of the master.

If diamond machining is the chosen process for the production of precise geometrical features and low roughness surfaces, copper or aluminum alloys are the obliged choice. These alloys are both suitable for diamond machining and subsequently for selective etching after electrodeposition.

For the purpose of the test CW008A oxygen free copper was preferred over aluminum for several reasons.

First it has higher thermal conductivity that helps to dissipate excessive heat accumulated during 3D printing. Second, the nickel coating can be deposited directly on the copper surface without any intermediate layer- which is necessary in case of aluminum. Third, the low amount of impurity in the alloy (0.05%), will prevent redeposition of impurities on the nickel surface once the copper is etched away.

Three copper cylinders 25 mm in diameter were polished down to nano-metric roughness, figure 3a. The Sa surface roughness was measured by means of confocal microscopy. After chemical dissolution of the master, subsequent comparison with the roughness of the nickel deposit will indicate if any grain growth occurred.

3.2. Electroplating

Electroplating of the masters were performed in a proprietary nickel-sulfamate bath. Before the electroplating process, the copper samples were degreased in alcohol and weighted on a precision scale. Subsequent measure of the weight gain will help estimating the average thickness of the nickel coating.

After a short dip in a commercial solution to remove the oxide layer, the copper part was submerged in the nickel sulfamate bath kept at a constant temperature of 36 °C and a DC current of 1.3 A/dm² was applied. These particular settings ensure a deposition rate of 15 µm/h generating a low-stress coating with good adhesion to the substrate. The master surfaces were masked with tape except for the top surface, which was facing the anode to maximize the nickel deposition efficiency. Three samples were coated simultaneously and measurements of the weight gain allowed calculation of average thicknesses of 459 µm, 431 µm, and 523 µm respectively for sample 1, 2 and 3. One of the coated samples is shown in figure 3b.

3.3. Deposition of the buffer layer

A thermal sprayed metallic layer was deposited on top of the electroformed nickel coating. Pure nickel and X40CrMoV5-1 steel were chosen as they both provide; strong adhesion of the thermally sprayed layer – which is essential to avoid delamination - and preliminary tests also showed good adhesion of these two materials with electroformed nickel. Sample 1 and 2 were coated with X40CrMoV5-1 steel while sample 3 was coated with pure nickel.

A 500 µm thick coating was applied in all cases on top of the samples and then machined down to 300 µm.

This ensure planarity of the thermally sprayed coating and, at the same time, gets rid of the first tens of microns which is known to have a high concentration of voids, (see figure 4).

3.4. 3D printing

3D printing tests were performed in a SLM machine EOSINT M 270 using EOS MS1 steel. The process parameters were carefully chosen to keep the maximum temperature in the electroformed layer below 250° C, which is the temperature at which it is believed that recrystallization of nickel begins.

The tests were conducted using a raster scan strategy moving the laser at 0.8 m/s, the laser power was set to 120 W, while the hatch distance to 100 µm.

Even though full density of the 3D printed structure (above 99.5 %) is not reached, the residual porosity do not affect the surface finishing since the additive manufactured part will lay completely underneath the electroformed layer.

With the increasing of the thickness of the 3D printed structure, the deposition time, and thus the average temperature of the master increases as well. The copper master, during the deposition of the first few layers, is at a relatively low temperature and it acts as heat sink, effectively cooling down the electrodeposited nickel. The average temperature of the copper master though, raises with the deposition time and its heat evacuation properties decrease. With the heat accumulation, the temperature of the nickel layer can approach the recrystallization temperature and ruin the optical surface quality.

In order to assess the effect of the heat accumulation on the electroformed nickel layer, three different tests were carried out with increasing thermal input.

The first test, which will be referred as test 1, consists of a 3D printed structure 0.5 mm thick, deposited on top of the thermally sprayed X40CrMoV5-1 steel using 100 µm layers thickness for the printing process.

The second test, which will be referred as test 2, consists in a 10 mm structure with 80 µm layer thickness deposited on top of the thermally sprayed X40CrMoV5-1 steel, shown in figure 3c.

In the third test, referred as test 3, a 13 mm structure was built using again a layering of 80 µm, on top of the thermally sprayed pure nickel and subsequently machined to fit as insert in a mould for injection moulding.

3.5. Copper etching

After the 3D printing process, the thick copper substrate was removed by a combination of mechanical and chemical removal processes. To avoid prolonged stay of the sample in the copper stripping solution, the copper master was machined down to 500 µm thickness and dipped in the copper stripper solution afterward. All the steel parts were accurately masked. Sample 3 is shown after etching and machining of the 3D printed part in figure 3d.

3.6. Roughness and hardness measurements

The Sa roughness of the samples were measured in four different points. The measurements were taken before coating on the copper samples, and after copper stripping on the electroformed nickel. An Olympus LEXT OLS 4100 was used using an objective lens of 50 X magnification.

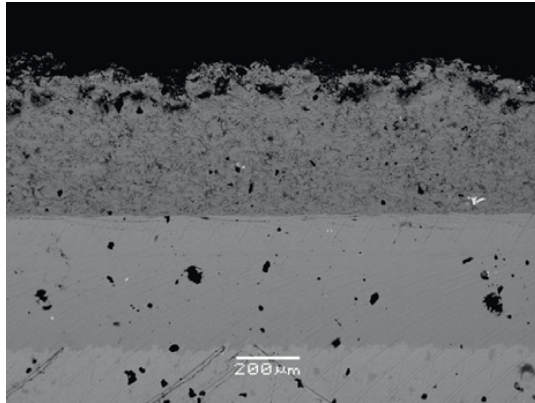


Fig. 4. Back scattered electron image of a cross section of sample 1. From bottom to top it is possible to distinguish: the copper master, the electrodeposited nickel and the X40CrMoV5-1 thermal sprayed layer. The black spots on the nickel and copper layer are dust particles due to insufficient cleaning of the sample.

For every sample, four different areas $250\ \mu\text{m} \times 250\ \mu\text{m}$ were acquired in the proximity of the central mark engraved on the copper sample and replicated on the electroformed nickel deposit. The data were post processed using SPIP image metrology, removing planar tilt and spikes coming from the 3D acquisition.

The hardness measurements were performed on the electroformed nickel surface produced in test number 3, were the thermal load is higher and therefore more critical.

A Vickers indenter was used for micro-hardness measurements of the sample. Six different indents were performed using 200g of indentation load and measured using a 100x magnification lens.

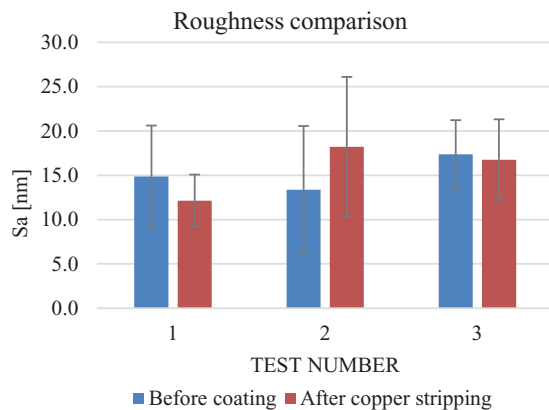


Fig. 5. Comparison of surface roughness of the master (blue) and the correspondent nickel surface (in red). TEST NUMBER is referred to the tests described in paragraph 3.4.

4. Experimental results

4.1. Roughness measurements with comparison

The results of the roughness measurements are shown in figure 5. The histogram shows the comparison between the copper master and the corresponding nickel surface after the master chemical dissolution for the three samples used in the tests. Slight variations of the roughness of corresponding surfaces are considered not significant since they are within the random variability of the measurement (1σ) and they do not show any recognizable trends. The introduction of the buffer layer is effective in maintaining the temperature of the electroformed nickel, as a consequence of the thermal input of the 3D printing process, to values lower than the nickel recrystallization temperature. The choice of the buffer layer material (pure Ni or X40CrMoV5-1) does not affect the measured roughness of the electroformed nickel layer, which is in the range of 15 nm for all the three tests (see figure 5), demonstrating the lack of recrystallization. The different layer thicknesses and deposition time of the 3D printed structures used in tests 1, 2, 3 do not significantly alter the roughness of the electroformend surface. The heat input of the 3D printing process is dissipated quickly enough in all the three tests, preventing excessive temperature raise and therefore recrystallization.

4.2. Hardness measurements

Another indication of grain growth would be significant changes in the hardness of the nickel deposit. It is well known that the micro hardness of polycrystalline materials can be related to the grain size according to the Hall-Petch equation [11], therefore hardness measurements were performed after the 3D printing process and compared with measurements reported in the literature on nickel deposits from a similar electrolyte [12]. The values were measured following the procedure describe in paragraph 3.6 and they are shown in table 1. Close agreement in terms of HV_{200g} , suggests that the initial grain size - and thus the hardness - of the electroformed nickel remained unchanged during the whole process chain.

Table 1. Comparison of micro hardness of electroformed nickel coatings.

	Reference [12]	Test 3
HV_{200g}	476	$496 \pm 9 (1\sigma)$

5. Conclusion and future work

In this paper, an innovative process chain was presented. The aim of the process chain is to produce moulds and dies coupling electroforming with 3D printing in a synergistic way; the high surface finishing achievable by means of electroforming is coupled with the higher production output - and the possibility of creating conformal cooling channels - provided by selective laser melting.

The proposed process chain shows the capability of producing optical quality moulds with reduced process time. The characteristic of the electroformed coating remains intact

during the process chain, retaining the low roughness level and good hardness values of electroformed nickel.

Future work aims at testing the produced insert in an actual injection moulding set-up and coupling electroforming with direct metal deposition processes (cladding).

Acknowledgements

The work in this paper has been supported by MADE Manufacturing Academy of Denmark

References

- [1] A. Armillotta, R. Baraggi, and S. Fasoli, "SLM tooling for die casting with conformal cooling channels," *Int. J. Adv. Manuf. Technol.*, vol. 71, pp. 573–583, 2014.
- [2] J. Kruth and M. Badrossamay, "Part and material properties in selective laser melting of metals," in *Proceedings of the 16th International Symposium on Electromachining (ISEM XVI)*, 2010, pp. 3–14.
- [3] K. W. Dalgarno and T. D. Stewart, "Manufacture of Production Injection Mould Tooling Incorporating Conformal Cooling Channels via Indirect Selective Laser Sintering," in *Proceedings of the Institution of Mechanical Engineers, Journal of Engineering Manufacture*, 2001, vol. 215, no. 10, pp. 1323–1332.
- [4] G. Bissacco, P. T. Tang, H. N. Hansen., B. A., and C. Holme, "Suitability of Electroformed Nickel Moulds for Wafer Based Precision Glass Moulding," in *Proceedings of the 8th International Conference on Multi-Material Micro Manufacture*, 2011, pp. 125–128.
- [5] H. N. Hansen, M. Arentoft, P. T. Tang, G. Bissacco, and G. Tosello, "Tooling process chains and concepts," in *Micro-Manufacturing Engineering and Technology*, First Edit., Elsevier Ltd., 2010, pp. 287–297.
- [6] G. Tosello, H. N. Hansen, S. Gasparin, and I. Esmoris, "Surface wear of TiN coated nickel tool during the injection moulding of polymer micro Fresnel lenses," *CIRP Ann. - Manuf. Technol.*, vol. 61, pp. 535–538, 2012.
- [7] P. T. Tang, J. Fugl, L. Uriarte, G. Bissacco, and H. N. Hansen, "Indirect tooling based on micromilling, electroforming and selective etching," in *4M2006: Second International Conference on Multi-Material Micro Manufacture*, 2006, pp. 183–186.
- [8] J. A. McGeough, M. C. Leu, K. P. Rajurkar, A. K. M. De Silva, and Q. Liu, "Electroforming Process and Application to Micro/Macro Manufacturing," *CIRP Ann. - Manuf. Technol.*, vol. 50, no. 2, pp. 499–514, 2001.
- [9] G. Bissacco, H. N. Hansen, P. T. Tang, and J. Fugl, "Precision manufacturing methods of inserts for injection molding of microfluidic systems . Technical University of Denmark," in *Unknown*, 2012, pp. 1–7.
- [10] L. Æ. Uriarte, A. Herrero, A. Ivanov, H. Oosterling, L. Staemmler, P. T. Tang, and D. Allen, "Comparison between microfabrication technologies for metal tooling," in *Proceedings of the Institution of Mechanical Engineers Part C-journal of Mechanical Engineering Science*, 2006, vol. 220, pp. 1665–1676.
- [11] G. D. Hughes, S. D. Smith, C. S. Pande, H. R. Johnson, and R. W. Armstrong, "Hall-petch strengthening for the microhardness of twelve nanometer grain diameter electrodeposited nickel," *Scri. Metall.*, vol. 20, no. 1, pp. 93–97, 1986.
- [12] P. T. Tang, "Pulse reversal plating of nickel and nickel alloys for MEMS," in *Proceedings SUR/FIN*, 2001, vol. 47, pp. 224–232.